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Do bound color octet states of liberated quarks exist?

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In models where quarks are liberated and color can be excited, the three-quark color-octet state is shown to be unbound and unstable against breakup into free quarks and diquarks. The signature for color excitation in deep inelastic processes should not be a bound three-quark state which decays electromagnetically but a final state containing free quarks.

The production of color octet states has recently been suggested[1] as an explanation of an apparent new threshold in deep inelastic muon scattering.[2] But the usual models based on colored gluon exchange which explain the binding of color singlet quark-antiquark and three-quark systems[3,4,5], predict that color octet states are not bound but immediately break up into quarks and diquarks.[5,6,7] Thus an experiment which excites color should not produce a long-lived bound state which decays electromagnetically and gives a hard photon signal.[1] The state should break up into hadrons and either a liberated quark-antiquark pair or a liberated quark-diquark pair. These new peculiar objects should then decay weakly if they have integral electric charge. If they have fractional charge the final state must include stable fractionally charged particles.

The colored gluon exchange models may be inadequate, but they are the only models that predict that only three-quark and quark-antiquark color singlet states should be bound and that there is no bound I=2 dipion state. Since these predictions agree with experiment for the color singlet sector, the corresponding predictions for the color octet sector can be assumed to have a reasonable validity. Furthermore, this prediction that there are no strongly bound quark-antiquark or three-quark states in the color octet sector, also follows from the intuitive argument that any model with vector gluons should give a Coulomb-type repulsion between two identical quarks of the same color. This is discussed in detail below.

If the qualitative results of Refs. 3-7 regarding the sign of the interaction are not accepted, the field is wide open. There is then no theoretical prediction at all for which states should be lowest in the color octet sector and no reason to expect an electromagnetic decay with a hard photon. No model predicts that a three-quark color-octet state should be bound. If other unknown effects are strong enough to reverse the sign of the Coulomb repulsion between two identical quarks the lowest color octet state might be a state of nine quarks.

The essential physics in the argument can be seen from the analogy with QED. The electron-positron force is attractive, but the electron-electron force is repulsive. Thus QED gives bound states of positronium, but no bound states of two electrons. Note that these properties of the forces are already required from experimental information on the positronium spectrum and the absence of strong binding forces between two positronium atoms, even without direct measurments on electrons and positrons. The electron-positron force must be attractive to bind positronium. The electron-electron and positron-positron forces must be repulsive to cancel the attractions between the electron in one positronium atom and the positron in the other and thus prevent the strong binding of four-lepton systems.

From the description of pions as bound quark-antiquark systems and the observation that there is no bound state of two positive pions with charge +2, we similarly conclude that the $q\bar{q}$ force must be attractive to bind the pion, but that there must be repulsive forces in the two-pion system to cancel the attractions between a quark in one pion and the antiquark in the other. However, the qq force cannot be totally repulsive because quarks are bound in baryons. This paradox has been solved[5] by the introduction of three colors and the non-abelian colored gluon exchange interaction. This interaction is attractive between a red quark and a red antiquark and repulsive between two identical red quarks just like photon exchange forces between electrons in QED. But a red quark and a blue quark have an attractive force in the antisymmetric color triplet state, as a result of a color exchange force in which the two quarks exchange colors by exchange of a colored gluon. Thus there is attraction and binding in a diquark and in the three-quark baryon if the quarks have different colors and the states are antisymmetric in color. The force between two quarks of the same color remains repulsive and mesons and baryons behave like neutral positronium atoms and do not bind additional quarks. A state of two red quarks and a blue quark will not bind but will dissociate into a red-blue diquark and a red quark.

The color octet state created in the absorption of a color octet photon by a baryon still has only one red, one white and one blue quark and does not have two quarks of the same color. However, it has the color octet symmetry and is in the same color multiplet as the states with two red quarks and a blue quark. Since color is a good symmetry of strong interactions, all states of the color octet must have the same mass. Thus if the state with two red quarks and a blue quark has a mass above the threshold for breakup into a quark and a diquark, all states in the octet are unstable against such a breakup.

In the approximation of a one-gluon-exchange potential which gives the static Coulomb interaction in QED, the argument against stability of color octet baryons is rigorous.[5-9] The values of the strengths of the interactions for one gluon exchange have been tabulated in Ref. 5 and show that the color analog of the Coulomb interaction between a quark and a diquark is repulsive in the color octet state and will not give bound states. The validity of simple one-gluon exchange can be questioned for describing complicated strong interactions in detail, but should give qualitative results regarding the sign of the interaction. Without a complete theory of the bound states of liberated quarks, no rigorous conclusions are possible. However, semiquantitative plausibility arguments can be given which present a physical picture and suggest that higher order corrections should not reverse the sign of the force between two identical quarks.

In the analogous case of QED, the electric field of an electron-positron system consists of lines of force joining the electron and positron. As the distance between the two is increased, the field is spread out over a larger volume and its energy increases. The energy in the field is minimized by putting the two particles at the same point and canceling out the field entirely. Thus the electron-positron force is attractive. The electric field of two electrons has no lines joining the two but has all lines from each electron going out to infinity. The energy in the field is minimized by separating the two by an infinite distance; it is maximized by putting the two electrons at the same point. Thus the electron-electron force is repulsive.

Let us now compare the energies in the color fields of two quarks of the same color when they are at the same point in space and when they are separated by a very large distance. Since we assume that quarks can be liberated, the color field of a quark must go to zero at large distances. Let $E(g)$ be the energy in the color field of a point color charge of magnitude g. Then the energy in the color fields of two widely separated quarks of the same color and charge g is $2E(g)$. If the energy in the field of the two quarks increases as they are brought together to a value considerably greater than $2E(g)$, there must be a repulsive force between the two quarks. In the static Coulomb approximation, in which the electric field of a point charge is proportional to the charge, the energy in the field is proportional to the square of the charge. The energy of two quarks brought together at the same point is $E(2g)$, which in this approximation is

$$E(2g) = 4E(g) > 2E(g) \tag{1}$$

Thus the force is strongly repulsive as in the case of two electrons.

Higher order corrections to the color field of a point color charge can change this result. However a drastic change is needed to reverse the conclusions from Eq. (1). The condition that two quarks should have an attraction between them is that the energy should decrease to less than 2E(g) as they are brought together,

$$E(2g) < 2E(g) \tag{2}$$

Although higher order corrections may modify the first order result (1) it seems highly unlikely that they should make the dependence of energy on charge so peculiar as to satisfy the relation (2). This would be equivalent to reversing the sign of the electron-electron interaction from repulsive to attractive as α is increased. Although this argument is not rigorous, it is certainly sufficiently plausible to suggest that any attempts to analyze experimental data to look for liberated color should assume that such states will in all probability not remain bound but will break up into quarks and diquarks.

A quantitative and rigorous result on the instability of color octet baryons in the one-gluon-exchange approximation is obtainable from the mass formula of Nambu's first paper discussing the binding of colored quarks into hadrons by the exchange of an octet of colored gauge bosons.[3] Nambu's mass formula, which used only the group theoretical aspect of the interaction and not its spatial dependence, showed that only color singlet states of the 3q and $q\bar{q}$ configurations were absolutely stable; i.e. that their masses were lower than all possible decay products. The exotic color singlet states were borderline cases, with masses exactly equal to the sum of the masses of possible decay products. Thus whether or not an exotic $qq\bar{q}\bar{q}$ state was stable or not against decay into two mesons depended upon smaller higher order effects. The non singlet states were all highly unstable, except for the diquark, with a mass much higher than the mass of possible decay products. Thus the small effects which might bind the color singlet exotics would not bind non singlet states, such as color octets. This model was extended in Ref. 5 to consider the spatial dependence of the interaction and spatial wave functions for the color singlet exotic states and showed that they would not be bound as a result of spatial correlations.

A treatment of spatial configurations for three-quark color-octet states similar to that of Ref. 5 for the $qq\bar{q}\bar{q}$ system gives a similar result that binding is not produced by spatial correlations with reasonable forces. The introduction of spin dependent forces might lead to weakly bound states analogous to the exotics predicted by Jaffe but not yet found.[10] Such states would be expected to have only a small binding energy of the order of several hundreds of MeV. Their production threshold would not be easily distinguished from the threshold for the production of free quarks. Thus even if peculiar bound states exist, they are not relevant for the experimental result of Ref. 1. They would not be produced appreciably because of poor overlaps in the wave function with normal baryons, and experiments above their production threshold should produce free quarks much more strongly. Thus if the new threshold observed experimentally is indeed the production of color octet states, the final states produced should be investigated for signature of free quarks.

These arguments apply also to the Pati-Salam model,[11] which was used as a basis for the calculations of Ref. 1 and which discuss in detail the properties of individual quarks and leptons, including the "new physics" of their model which includes liberated quarks and quark decays into leptons. But they do not specifically treat the binding of quarks into hadrons, and implicitly assume the conventional "old physics" of hadron spectroscopy, as treated in Refs. 3-5.

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